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Flood-related risks in Ho Chi Minh City and ways of mitigation

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ABSTRACT

With an ever-growing population of around 10 million inhabitants (officially 7.9 in 2013), Ho Chi Minh City (HCMC) is set to become one of the largest cities in South East Asia and already occupies a major economic role in the area. To accommodate the increasing population, the megacity now stretches out in an urban continuum covering more than 800 square kilometers and is currently growing at a rate of 3.2% per year. If the neighboring provinces around HCMC are included, the total population reaches nearly 18 million people.

This paper attempts to describe the interplay between HCMC and flood-related risks and offer some guidelines to deal with inundations. The potential risks of flooding by rain, tsunami and/or dam failure upstream of the city are evaluated and contextualized within the perspective of climate and human-induced environmental changes. The region is highly vulnerable to the combined effects of subsidence and rising sea levels and has already led to serious flooding that may extend spatially before the end of the century. We propose possible preventative solutions to urban flooding using a multi-pronged approach to issues regarding urban development and suggest a redevelopment strategy for major infrastructure projects.

1. Introduction

Ho Chi Minh City is a low elevation coastal megacity with a very large and rapidly increasing population. Economic activity is also very high and rising in line with the population increase. Like most megacities in South East Asia or India that were built within a delta's boundaries, HCMC is affected by flood related risks aggravated by the conjunction of heavy rains and high tide levels. This situation is driven by three factors: low elevation of the land above sea level, extensive urban growth yielding to soil subsidence, and an extension of impervious areas resulting in increased runoff (Tran Ngoc et al., 2016).

Over the last 300 years, HCMC has gone through several phases of expansion. Because the city is bordered by the Saigon River and intersected by several creeks, water has always been a fundamental part of its identity. In the late 18th and early 19th centuries, the Nguyen Dynasty expanded the canal network to improve waterway transportation and facilitate commercial activity. Under French rule in the first half of the 20th century the urban face of Saigon underwent major changes, in particular the canals intersecting the city center were filled to create tree-lined boulevards (Ton and Truong, 2011). Swampy areas were also filled to build residential areas and concomitantly, the network of remaining canals was progressively used as an open-air sewage system (domestic as well as industrial waste water) (Givental, 2014). Water is now the main focus of all worldwide climate-related issues and HCMC finds itself on the top-ten list of cities categorized as being in the greatest danger of coastal flooding (Small and Nichols, 2003; ISPONRE, 2009).

This paper proposes a multiple perspective approach to characterize the principal risks of flooding caused directly by heavy tropical rain and runoff and/or high tide wave-set-up, and ways to mitigate them. First, field measurements were taken throughout the urban area to quantify flooding by rain and to assess the flood risks in those neighborhoods. This quantification is complemented by numerical simulations to characterize the risks of submersion caused by either tsunami waves or the rupture of a dam as well as data related to the expected increase in future sea levels. Once the main results of these flood related risks are cross-referenced

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and assessed we discuss possible urban planning for Ho Chi Minh City's future development.

2. Materials and methods

2.1. Study site

HCMC is located in a low-elevation coastal zone in the upper border of the Mekong Delta and 65% of its territory is at an altitude below 1.5 m above sea level (Fig. 1). It is characterized by a subtropical monsoon climate with two distinguished seasons. The rainy season extends from May to November with a heavy period from September to October. In total, about 160 rain events occur yearly with an average cumulated rainfall of roughly 2000 mm. Because of the convective pattern of precipitation events, the rain is non-uniformly distributed at the scale of the megacity, with considerable differences from one district to another for a given storm event. This variability at short spatial scale is currently not accounted for in weather forecast reports. In conjunction with heavy precipitation, HCMC is also affected by the combined effects of semi-diurnal tides waves, with amplitude reaching a maximum of 1.5 m, and high water discharge from both upstream rivers; namely the Saigon and Dong Nai rivers.

HCMC has been experiencing severe accelerated urbanization since the start of the last decade with up to 100% of land surface constructed upon in some sectors (Nguyen, 2013). Heavy rain intensity and lack of sewage infrastructure makes the megacity highly vulnerable to flood risk. As shown in the present study, the spatio-temporal dynamics of flooding in HCMC differs significantly when driven by rainfall or river overflow.

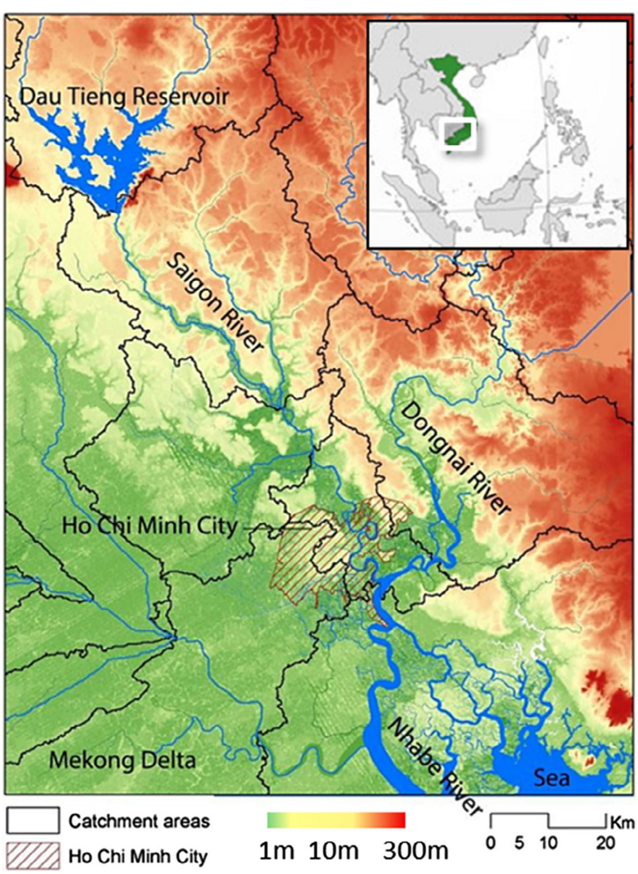

Fig. 1. Elevation Map; the green color corresponds to an altitude lower than 1.5 m (reproduced from Nguyen (2013) with the agreement of the author). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Monitoring rain and flood zones

Since 2002, a monitoring network has been developed to survey urban flooding at the street scale and includes 11 automatic rain gauges distributed all over the city as well as monitoring cameras installed in 2013. This network is completed by visual observations to characterize the submerged areas, i.e., to measure water depth, duration and spatial extension of any inundations. Since 2009, inundation areas have been systematically classified into two typologies: submerged areas are referred to as "old" for those that are regularly submerged from year to year, or "new" for those appearing in different locations from year to year.

2.3. Numerical modeling

To assess another risk of flooding by tsunami or dam failure, numerical simulations were undertaken with Telemac2D code (Lang et al., 2010). This software is based on the Barré de Saint Venant equations and assumes 2D shallow water conditions. Initially developed by Electricité de France (EDF), it was chosen for its ability to solve large-scale problems with reasonable computation time.

The first case study aimed to evaluate the effects of a tsunami that could occur due to an ocean quake (with different levels) in the East Sea: a potential earthquake area because of its geological structure. Hypothetical numerical runs were conducted by placing the epicenter about 240 km from Vietnam's south coast. The purpose was to determine the spatio-temporal characteristics of tsunami waves and help authorities set up early warning procedures. As presented in Fig. 2a, the numerical domain extended up to HCMC. The discretization scheme consisted of 1,045,000 triangular elements, varying in size from 500 to 4000 m for the seaward extension of the domain to a size of 10 m to describe the streets in the urban context. Different cases of earthquake magnitude corresponding to 7.6, 7.8, 8.0, and 8.35 on the Richter scale were simulated. It took one hour of computation to simulate ten hours using an Intel server cluster on parallel mode with 16 cores.

The second case study was undertaken with the same numerical model and grid of discretization, but focused on the domain located upstream of HCMC. It aimed to assess the city's submersion risk in the event of the Dau Tieng dam failure, which is located eighty kilometers upstream of HCMC. This earth dam was constructed between 1981 and 1985 for agricultural irrigation in the provinces surrounding HCMC and has a total capacity of 1.58 billion m^3 of water and maximum water level of 28 m. The study area (Fig. 2b) extended from the Dau Tieng Lake to the estuary and represented a surface of 5000 km^2. It was discretized with 270,000 triangular elements. The simulation was done for a failure width of 500 m, corresponding to a maximum instantaneous flow discharge of 40,000 m^3/s in a section located ten kilometers downstream of the dam.

3. Results and discussion

3.1. Coupled effects of rainfall and urbanization

Fig. 3a represents the number of storm events observed in HCMC from 2007 to 2014 and demonstrates that heavy rain events exceeding 100 mm are not rare and can be observed every year. However, important inter annual variability can also be observed.

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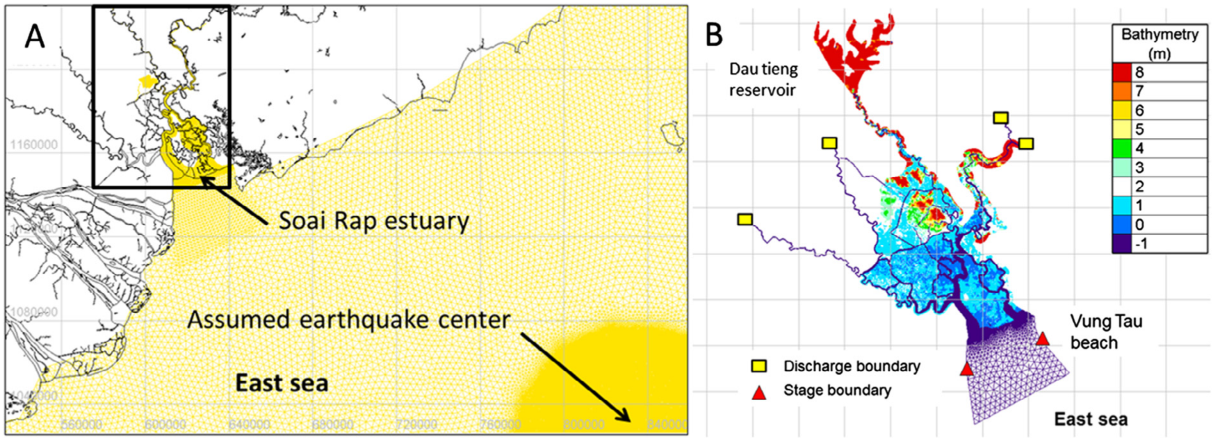

Fig. 2. Description of the numerical grid domain for the simulation of tsunami waves (A) and dam failure flood (B).

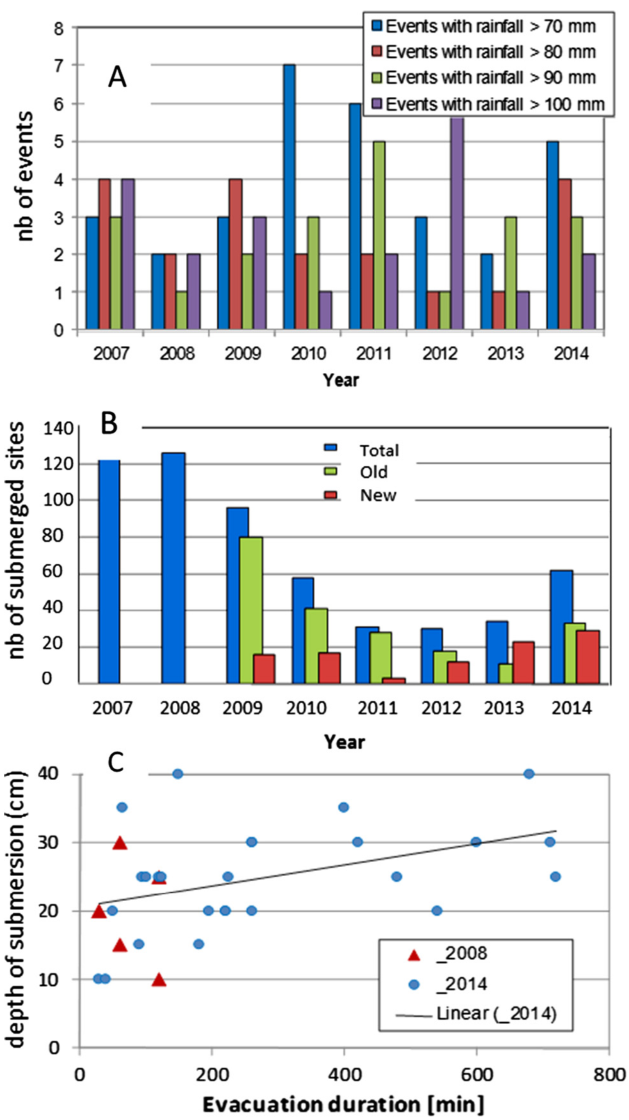

Fig. 3. Flooding by rain in HCMC. A) Number and typology of rainfall events, from 2007 to 2014; B) Number and typology of submerged areas, from 2007 to 2014; C) Impact of urbanization for Kinh Duong Vuong district from 2008 to 2014 on the length of time for flood recession to occur.

Another important result is that some locations are systematically submerged, yet each year new flood sites can be observed (Fig. 3b). The total number of submerged locations was the highest in 2008 (126 locations), as a result of a very sharp increase in building density since the beginning of the 1990s. During this period, the impervious surface increased 8-fold in the flood-prone area and the population increased by 2-fold (Nguyen, 2013). This figure also shows that the number of submerged sites changed considerably over the 2008–2015 period. First, it decreased steeply from 2008 to 2011 to reach a minimum of 30 inundated sites. This can be related to the reduction from 4 to 1 of rainfall events larger than 100 mm (Fig. 3a), and also to large scale restructuration of the drainage infrastructure in the downtown area (Tran Ngoc, 2015). The resurgence of flooding observed in 2013–2014 is likely due to the development of peri-urban zones with poor sewer installation and poor maintenance, and to the increase of rainfall events.

It also seems that the time needed to reduce flooding (by drainage infrastructure) in the areas transitioning from small houses and gardens in 2008 to full urbanization in 2014 was much longer than anticipated, as illustrated in Fig. 3c.

Another consequence of intensive urbanization is that soil subsidence has reached a rate of 0.02–0.04 m/yr in some sectors and is illustrated in Fig. 4a. Similar observations were obtained by Ho Tong et al., 2015. This subsidence is greatest in the city center along the Saigon River (districts 7, 12, Binh Thanh, Thu Duc) and in the southwest peri-urban sectors (districts 6, 8 and Binh Chanh). In these sectors, old traditional houses have been demolished to make way for high-rise buildings (some of them more than 50 floors) and commercial centers. Subsidence here is the result of intensive groundwater pumping to secure building basements and is also linked to the construction of a new underground metro system due for completion in 2019. Dinh et al. (2015) also demonstrated the impact of geology because the most severe rates of subsidence were observed in the Holocene silt loam areas along the Saigon River and in the southwest of the city. It is obvious that this process leads to an accumulation of runoff and limits the evacuation by gravity of the flooded zones.

Overall, it is clear the city has several flood-prone areas with submersion levels varying from 0.15 to 0.65 m (Fig. 4b – produced by the Earth Observation Service of ESA) resulting from rainfall variability and/or high tide wave set-up and that both are impacted by subsidence. Comparison between Fig. 4a and b clearly demonstrates this conjunction between subsidence and flooding.

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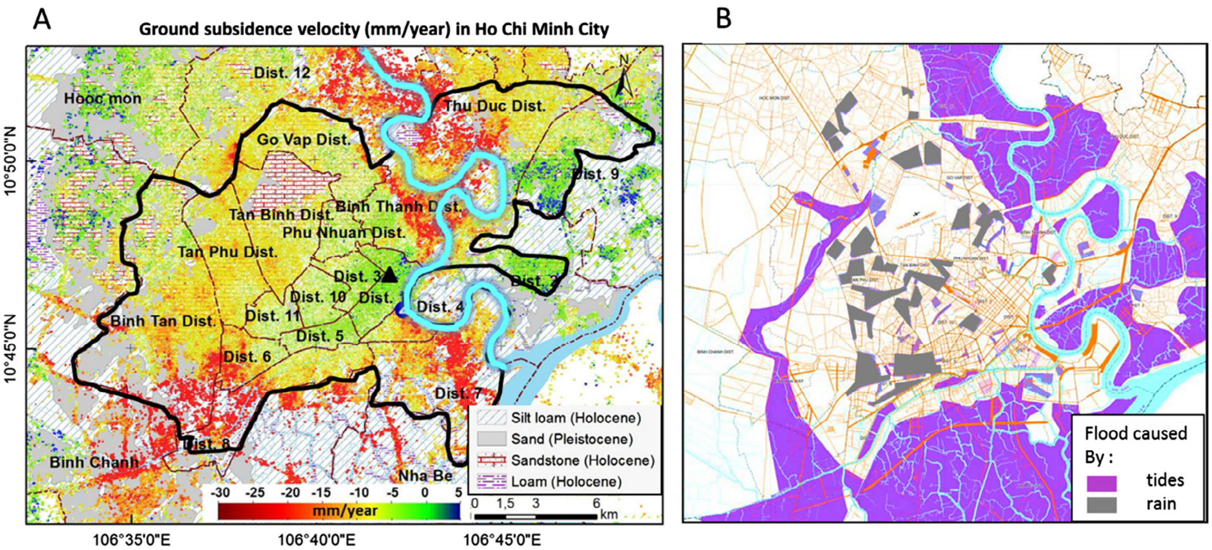

Fig. 4. A – Historical Mapping of subsidence rate produced by radar interferometry from the Satellite Observation; Subsidence rate – red = higher than 0.020 m/yr (by Dinh et al., 2015); B – Map of flooding probe areas caused by high tide wave set-up or by rain (from Koudogbo et al., 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Incidental flooding driven by wave propagation

Two numerical simulations were performed to determine the flood risk for several districts along the Saigon River that could result in wave propagation originating from either a tsunami in the East Sea or a reservoir dam failure upstream of HCMC, respectively.

For a quake reaching an intensity of 8.0 on the Richter scale, the average celerity of a tsunami's waves from the earthquake's epicenter to the estuary is about 20.5 m/s. The change in sea level height after 1.5 h is presented in Fig. 5a. The tsunami's peak arrives at the estuary after approximately 3.25 h and here the highest water level attains seven meters. The wave reaches downtown HCMC after an additional 4.5 h (Fig. 5b) and induces a wave between 1.5 and 3 m above the initial street level according to the different simulations considered. It is worth noting that during propagation along the mangrove fringe, tsunami waves could be greatly dissipated by this type of ecosystem (Barbier et al., 2008). It was not possible to include this mitigating effect in our simulation but it should be taken into consideration in the future.

The second case study of failure at the Dau Tieng dam is presented in Fig. 6. The flood wave has an amplitude that decreases rapidly from a peak of nearly 18 m at 20 km downstream of the dam to less than one meter in the city center. As shown in Fig. 6, the fluctuations due to tidal forcing (dashed black line) are comparable to those related to the impact of dam failure (solid black line). From this, it seems clear that HCMC is moderately vulnerable in the event of dam failure at Dau Tieng. The existence of a floodplain located upstream of HCMC where discharged water can spread may explain these simulated results. While the spread would protect HCMC's infrastructure and inhabitants, it would undoubtedly cause major damage in the upstream agricultural zones.

The conclusion that can be drawn from these simulations is that the risk of flooding from a tsunami would most likely be much larger than from dam failure.

3.3. Long-term vulnerability

A realistic flood risk assessment and its long-term evolution should also take into account the effects of human-induced climate change. A series of scientific works coordinated by the Intergovernmental Panel on Climate Change (IPCC) and summarized in its 5th IPCC Report (part 2, Impact, Adaptation and Vulnerability, March 2014) underlines that without a drastic reduction (50%) in green-

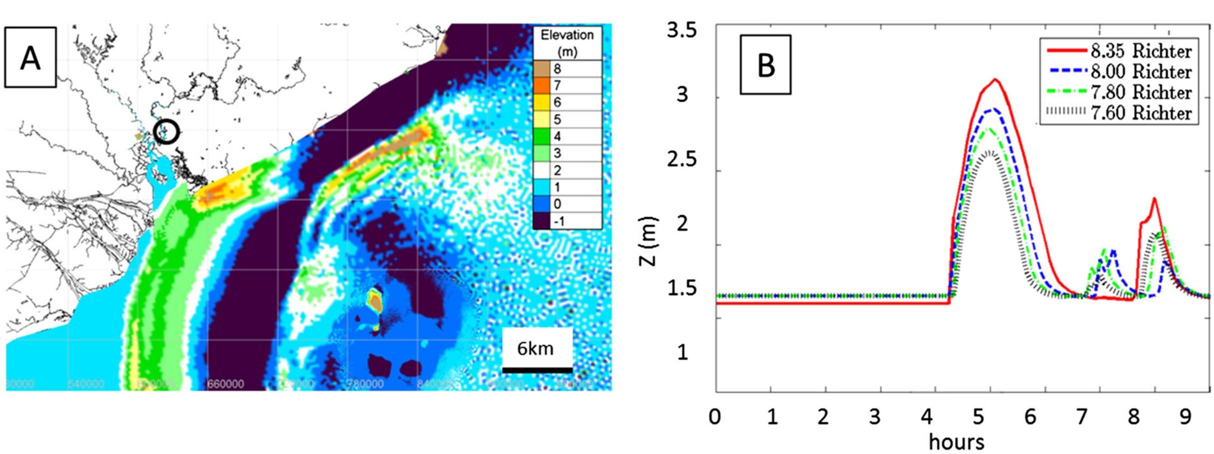

Fig. 5. Simulation of impact of tsunami, A – Propagation of tsunami wave 2.5 h after quake force 8; B – Stage of wave produced by tsunamis of various amplitude within the downtown area of HCMC.

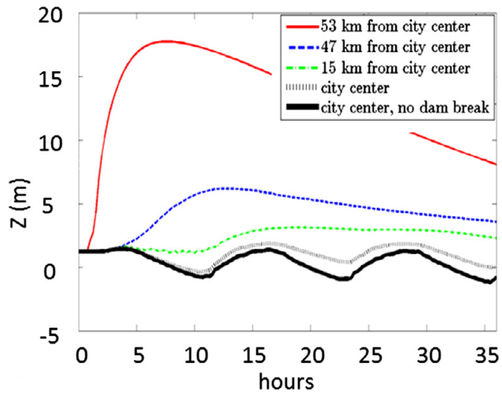

Fig. 6. Simulation of impact of dam failure: flood wave at different locations upstream from city center.

house gas emissions, the area of South Vietnam could be seriously affected by the conjunction of two effects:

- from a hydrometeorological perspective, an increase in the occurrence of typhoons and extreme rainfall (by 10–20%) is anticipated, with a strong impact on river flow and riverbank erosion.
- from an ocean perspective, an increase of the sea surface temperature to 30 °C or more in the South Pacific zone combined with the melting of Antarctica ice sheet could produce a sea-level rise of 1 m by the end of this century if greenhouse gas emissions continue unabated, as recently analyzed by de Conto and Pollard (2016) on the basis of innovative numerical simulations coupling ice sheet and climate dynamics.

The situation will certainly be exacerbated by the impact of human activities on soil subsidence at both the urban and regional scale. In addition to the megacity situation discussed in Section 3.1 and presented in Fig. 4, agricultural practices in the Mekong Delta are responsible for a very worrying situation, as pointed out by Erban et al. (2014). Through a set of observations obtained by satellite radar imagery over the delta from 2006 to 2010, the authors clearly highlighted a rate of soil subsidence varying between 0.02 and 0.04 m/year and an average decrease by 0.30 m per year of groundwater levels. A similar interplay between groundwater levels and soil subsidence was also reported by Dinh et al. (2014) for the HCMC region.

Consequently, the subsidence of soil at the regional scale could be higher than the rise in sea level by the end of this century. The cumulative effects could result in the lowering of the average soil level with respect to the sea level by 0.03–0.05 m/year; in other words, a 1.5–2.5 m rise in a 50 year period. The submersion of the quasi totality of the coastal fringe is to be feared: the loss of agricultural land (notably rice) due to salinization and the consequent migration of millions of inhabitants would have an enormous impact. A significant part of this migratory flux would probably be in the direction of HCMC, where large areas could also be submerged.

3.4. Urban planning strategy

In light of these results, it seems evident that to achieve sustainable development there needs to be revision of Ho Chi Minh City's urban development policies with a much greater emphasis on and integration of flood management strategies (ADB, 2010; VCAPS, 2013). For the time being, the city's rate of urbanization is advancing at an alarming rate, with former wetlands being filled and transformed into new development areas such as Phu My Hung and Thu Thiem. The megacity's continual expansion raises questions about the capacity of the soil to absorb runoff and its impact on floods (Kim and Ho, 2014). Since 2008, authorities in HCMC have been developing a Master Plan of coordinated urban expansion to be in place by 2025. This plan proposes the adoption of a multi-center city model with four major development areas and several additional urban projects. As can often be observed, there is a gap between planning and reality (ADETEF, 2012). Experts and local policy makers are in agreement that alternative measures need to be integrated (Lempert et al., 2013). In particular, investment in infrastructure needs to comply with land use policies, construction law and urban planning in order to implement the concept of a sustainable city at different scales. Furthermore, the development of urban areas alongside existing waterways and in low-lying swampy areas is met with institutional, technical and financial challenges.

At the institutional level, the challenge is to implement a coherent urban planning policy by breaking it down into national, regional and urban levels. It is crucial to promote a transversal approach (land use, urban planning and water management), to adopt a multi-scale vision, and to avoid single-sector and single-project approaches (Eckert and Waibel, 2009). At the technical level, development of relevant urban planning tools is required at the planning stage: environmental impact studies should be enforced to ensure sustainable water balance when a wetland site is filled. Setting-up monitoring networks and access to acquired data is a prerequisite to develop robust scenarios coupling measurement, statistics and numerical simulations. A further challenge concerns the need for innovative construction techniques adapted to the geology of particular sites. This would include the construction of underground works such as metro lines and basement parking areas.

These challenges have been debated during workshops with policymakers in order to consider the water-related problems of urbanization in an integrated way. For example, the rivers and channels in HCMC were long considered as being for transport only, but they are now also considered as recreational areas and important for the city's identity as they improve the quality of life for residents. Recent urban development projects in the HCMC metropolitan area have already brought major improvements by greening riverbanks and improving water quality in the creeks and Saigon River.

One of the main challenges for Ho Chi Minh City's future is to allocate more space to green and blue belts in planned layouts. Urban multi-functional basins (Fig. 7a) could respond to hydrological and environmental issues by preserving areas for storm water retention and storage of tidal flow volumes (rising tide). They could also integrate urban and landscape planning at different scales (PADDI, World Bank, 2014).

An integrated territorial approach needs to account for the specific context of the estuary and the city. It should connect sites with surrounding neighborhoods by prioritizing the entity of 'the park ' and enhancing the river embankment's value. This would help the city to adopt a more sustainable urbanization policy, particularly in the implementation of city water infrastructure projects, and to mitigate and reduce flooding hazards. In addition, upgrading and use of the water network will also create favorable conditions for the development of waterway transportation and river tourism. In 2012, the Centre de Prospective et d'Etudes Urbaines de Ho Chi Minh Ville (PADDI) proposed several courses of urban action relating to large civil engineering projects for dike network construction in order to reduce the risk of flooding, for example:

- Reducing flow velocity by facilitating the spread of the rising tide flow upstream.

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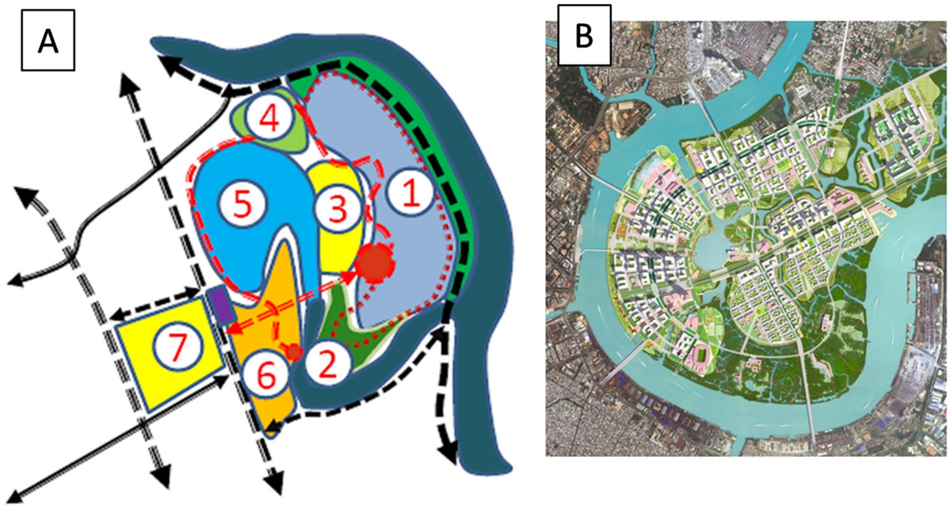

Fig. 7. A – Example of multifunction park, B – Proposal for the creation of new urban area of Thu Thiem.

- Developing storm water storage facilities away from tidal influence in order to reduce the discharge flow in sewage networks after a storm (or a dam failure) and the risks of overflow on roads at high tide.
- Facilitating rain water infiltration by preserving natural environments or installing storm water infiltration ponds.

A good example is the upcoming creation of a new urban area by the name of Thu Thiem, which is presently a swamp in one of the meanders of the Saigon River (Fig. 7b). The plan includes a residential area and large urban park that takes into account possible inundation and includes an artificial lake for water retention. Because of its strategic location just in front of the city center, Thu Thiem should have the capacity to mitigate tidal floods and high water events through man-made canals, lakes and mangrove areas and at the same time to accommodate over 130,000 residents.

4. Conclusion

The mitigation of water related risks is a priority for many megacities, especially those located in low-elevation tropical coastal areas. Considering the vulnerability of HCMC and its economic importance at the regional scale, a multidisciplinary approach has been adopted to evaluate the interplay between urban development planning and flood-related risks within the framework of natural hazards and of climate and human-induced changes.

In recent years, many studies have been conducted to assess the vulnerability of this megacity to rainfall induced flooding. Based on spatial monitoring of rainfall and of the flooded areas, the results showed that the risk is especially intense during building construction phases. Maintenance of the drainage network appears to be a simple and essential measure to ensure optimal functioning of properly sized sewers.

We further analyzed the risk of flooding by tsunami or dam failure. The numerical simulations undertaken show that HCMC is more vulnerable to inundation by tsunami than by dam failure. This asymmetric response of the watershed to wave propagation mainly results from topographic effects. In the event of a dam failure, wave energy would be rapidly dissipated by spreading out over the flood plain upstream of HCMC. The habitations and infrastructure of this rural region would undoubtedly be severely affected. In the case of a tsunami, wave energy would be amplified during its propagation into the river network. It is worth noting that the dissipation of wave energy during its landward propagation into the mangrove fringe has not been taken into account in the present simulation and could mitigate the effects presented in the simulations.

Recent satellite based observations of the megacity and of the Mekong Delta, have demonstrated that without a drastic reduction in greenhouse gas emissions the combination of both the effects of soil subsidence and the expected impact of climate change on rising sea levels could lead to submersion of a large part of the Lower Mekong Basin, including low elevation areas of HCMC within a period of 30–50 years.

The current Master Plan for HCMC will be revised in the next few years. As part of this process, the Department of Urban Planning and Architecture (DUPA) is currently working on methodology to integrate climate change issues into the new urban plan, especially to assign specific land use as a key adaptive instrument. An example of this new plan of action is that HCMC is also developing some sectorial measures to build retention basins in several districts, and to limit urban extension in the wetlands. It is clear that integrating sea defense services provided by mangrove areas should be a prerequisite to any planned seaward urbanization.

The development plans can only be efficient if there is coordination between national and local authorities as well as technical departments. The "Climate change Office", established in 2012, will undoubtedly play a major role in the implementation of measures to increase the resilience of the city.

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